VARIABLE RELUCTANCE GENERATOR

CROSS-REFERENCE TO RELATED APPLICATION

The subject matter of this application is related to the subject matter of British Patent Application No. GB 0301833.0, filed January 27, 2003, priority to which is claimed under 35 U.S.C. § 119 and which is incorporated herein by reference.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention generally relates to a reluctance machine operated as a generator. More particularly, embodiments of the present invention relate to the operation of a variable reluctance generator which is able to generate into a load without the use of active switches in its phase winding circuits.

2. Description of Related Art

The characteristics and operation of switched reluctance systems are well known in the art and are described in, for example, "The characteristics, design and application of switched reluctance motors and drives" by Stephenson and Blake, PCIM'93, Nürnberg, 21-24 June 1993, incorporated herein by reference. Figure 1(a) shows a typical switched reluctance drive in schematic form, where the switched reluctance machine 12 is connected to a load 19. The DC power supply 11 can be rectified and filtered AC mains or a battery or some other form of electrical storage. The DC voltage provided by the power supply 11 is switched across the phase

windings 16 of the machine 12 by a power converter 13 under the control of the electronic control unit 14. The switching must be correctly synchronized to the angle of rotation of the rotor for proper operation of the drive, and a rotor position detector 15 is typically employed to supply signals corresponding to the angular position of the rotor. The rotor position detector 15 may take many forms, including that of a software algorithm, and its output may also be used to generate a speed feedback signal. The presence of the position detector and the use of an excitation strategy which is completely dependent on the instantaneous position of the rotor leads to these machines having the generic description of "rotor position switched".

Many different power converter topologies are known, several of which are discussed in the Stephenson paper cited above. One of the most common configurations is shown for a single phase of a polyphase system in Figure 2, in which the phase winding 16 of the machine is connected in series with two active switching devices 21 and 22 across the busbars 26 and 27. Busbars 26 and 27 are collectively described as the "DC link" of the converter. Energy recovery diodes 23 and 24 are connected to the winding to allow the winding current to flow back to the DC link when the switches 21 and 22 are opened. A low-value resistor 28 is connected in series with the lower switch to act as a simple current transducer. A capacitor 25, known as the "DC link capacitor", is connected across the DC link to source or sink any alternating component of the DC link current (i.e. the so-called "ripple current") which cannot be drawn from or returned to the supply. In practical terms, the capacitor 25 may comprise several capacitors connected in series and/or parallel and, where parallel connection is used, some of the elements may be distributed throughout the converter.

Figures 3(a) – 3(c) show typical waveforms for two operating cycles of the circuit shown in Figure 2 when the machine is in the motoring mode. Figure 3(a) shows the voltage being

applied at the "on angle" θ_{on} for the duration of the conduction angle θ_c when the active switches 21 and 22 are closed. Figure 3(b) shows the current in the phase winding 16 rising to a peak and then falling slightly. At the end of the conduction period, the "off angle" θ_{off} is reached, the switches are opened and the current transfers to the diodes, placing the inverted link voltage across the winding and hence forcing down the flux and the current to zero. At zero current, the diodes cease to conduct and the circuit is inactive until the start of a subsequent conduction period. The current on the DC link reverses when the switches are opened, as shown in Figure 3(c), and the returned current represents energy being returned to the supply. The shape of the current waveform varies depending on the operating point of the machine and on the switching strategy adopted. As is well-known and described in, for example, the Stephenson paper cited above, low-speed operation generally involves the use of current chopping to contain the peak currents, and switching off the switches non-simultaneously gives an operating mode generally known as "freewheeling".

As is well known in the art, switched reluctance machines can be operated in the generating mode. A typical arrangement is shown in Figure 1(b), where the load 19 of Figure 1(a) becomes the prime mover 19', such as an internal combustion engine, supplying mechanical energy. The power supply 11 becomes an electrical load 11', accepting energy from the electrical machine 12 through the power converter 13. In general, the phase currents are mirror images (in time) of the phase currents in the motoring mode. Such systems are discussed in, for example, "Generating with the switched reluctance motor", Radun, Proceedings of the IEEE 9th Applied Power Electronics Conference, Orlando, Florida, 13-17 Feb 1994, pp 41 – 47, incorporated herein by reference. Figure 4(a) illustrates a flux waveform and the corresponding current waveform when the system is motoring and Figure 4(b) illustrates the corresponding

waveforms for generating. It will be seen from Figure 4(b) that the machine requires a "priming" or magnetizing flux to be established (along with the necessary current to support this flux) before the energy is returned to the DC link. In other words, some electrical energy is required from the DC link to prime the machine before it is able to convert a larger amount of mechanical energy back to the DC link.

Though there are many topologies used for power converters for switched reluctance machines, all of them use a certain number of active switches, and these switches represent a significant portion of the cost of the converter. Considerable effort over many years has been put into reducing the number of switches per phase.

SUMMARY OF THE INVENTION

According to one embodiment of the invention useful electrical power is generated by a variable reluctance machine without actuating conventional power switches. A bias flux is introduced into the magnetic circuit, the magnitude of which flux varies with rotor position. Generation is achieved by limiting the phase voltage to a magnitude below that otherwise induced in the phase by the bias flux. Thus, a method and apparatus for generating electrical power is achieved either without active switches being present in the power converter of the machine, or with power switches present but that are not being actuated, and therefore effectively not present, while this mode is in operation.

The difference in flux between the bias flux and that associated with the limited voltage represents a flux that has to be supported by a current, which is caused to flow in the phase winding. Hence embodiments of the present invention generate electrical power in the or each phase of the machine. The phase voltage is optionally limited by a semiconductor device, such

as a diode or diode bridge arrangement connected with the phase. In such a system the semiconductor device also serves to restrict the flow of current in the phase to one direction, thereby producing a usable rectified source of electrical power. Another device for limiting the phase voltage is a thyristor which is, of course, controllable as to the level at which it is commutated.

The flux in the magnetic circuit optionally is biased by means of one or more coils magnetically coupled to some or all of the phase windings of the machine. The excitation of the coil is optionally constant or variable. Another way of biasing the flux is to arrange a permanent magnet, or magnetizable element, in relation to the phase(s). The bias coil(s) or magnet is optionally located on the same member as the phase winding(s), typically the stator.

Embodiments of the invention have clear advantages in that they avoid the need to provide power switches in the way a conventional switched reluctance generator would require. The conventional power switches in a switched reluctance generator need not be present according to embodiments of the present invention. Alternatively, the mode of operation in accordance with embodiments of the present invention optionally is set up in a conventional switched reluctance drive system and used temporarily as one of a range of operating modes. For example, the drive for an electric vehicle or hybrid electric vehicle may include a switched reluctance drive as the, or part of the, prime mover. In such systems, the switched reluctance drive has been used both as a source of motive power and as a generator at appropriate times. Embodiments of the present invention allow the same drive to be used with the power switches simply rendered inactive, rather than not being present. This can lead to improved efficiency of operation.

In accordance with a particular form of the present invention there is provided a method

of operating a variable reluctance machine as a generator, the machine having at least one phase winding, the method comprising: creating a bias flux linking the or at least one phase winding; and limiting the phase voltage to a magnitude below that otherwise induced in the phase winding by the bias flux.

Embodiments of the invention also extend to a variable reluctance machine having a first part with at least one phase winding and a second part which is arranged to move relative to the first part to generate electrical power; means for creating a bias flux linking the or at least one phase winding; and means for limiting the magnitude of the phase voltage below that otherwise induced in the phase winding by the bias flux.

The phase voltage may be limited initially to zero volts. This may be done conveniently with the use of diodes to limit the phase voltage as referred to above. Furthermore, the diodes also serve to restrict the flow of current in the phase to one direction, thereby providing rectified output electrical power. Such a diode may be part of a rectifier circuit providing, for example, full-wave rectification.

The output of the variable reluctance generator according to embodiments of the present invention optionally is controlled either by controlling the generator speed, the bias flux created in the at least one phase, or the voltage across the DC link.

BRIEF DESCRIPTION OF THE DRAWINGS

Other aspects and advantages of the invention will become apparent upon reading the following detailed description of exemplary embodiments of the invention and upon reference to the accompanying drawings, in which:

Figure 1(a) is a schematic drawing of a prior art switched reluctance drive operating as a

motor;

Figure 1(b) is a schematic drawing of a prior art switched reluctance drive operating as a generator;

Figure 2 is a prior art excitation circuit for the switched reluctance machine of Figure 1(a) or (b);

Figure 3(a) is a phase voltage waveform for the circuit shown in Figure 2;

Figure 3(b) is the phase current waveform corresponding to Figure 3(a);

Figure 3(c) is the supply current waveform corresponding to Figure 3(a);

Figure 4(a) and Figure 4(b) show flux and current waveforms for motoring and generating respectively;

Figure 5 shows generating system according to one embodiment of the invention;

Figure 6(a) shows a schematic view of the laminations and windings of a switched reluctance machine, according to an embodiment of the invention;

Figure 6(b) shows a schematic view of the laminations and windings of another switched reluctance machine, according to an embodiment of the invention;

Figure 7 shows inductance, flux-linkage and voltage waveforms corresponding to one embodiment of the invention;

Figure 8 shows flux-linkage, voltage and current waveforms corresponding to an embodiment of the invention;

Figure 9(a) shows a modification of the circuit of Figure 5, according to an embodiment of the invention;

Figure 9(b) shows a further modification of the circuit of Figure 5, according to an embodiment of the invention;

Figure 10 shows a yet further modification of the circuit of Figure 5, according to an embodiment of the invention;

Figure 11 shows a set of waveforms corresponding to the operation of Figure 10, according to an embodiment of the invention;

Figure 12 shows a circuit combining elements of Figures 9(a) and 10, according to an embodiment of the invention;

Figures 13-15 show sets of waveforms corresponding to the operation of Figure 12 according to different operating conditions, according to embodiments of the invention; and

Figures 16(a) and (b) show delta and star connections of a variable reluctance generator according to an embodiment of the invention.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Figure 5 is a schematic diagram of one phase of a variable reluctance machine system according to one embodiment of the invention. The system may have only one phase or it may be polyphase. The components which are the same as in the prior art system of Figure 2 are given the same numerals. In addition, the machine has a bias winding 18 fed by a constant current source 20. The magnetic polarity of the bias winding 18 with respect to the phase winding 16 is denoted by dots. The current in the bias winding is I_b, and the voltage, V_b, induced in it by the phase voltage, V_{ph}, by virtue of its magnetic coupling, is given by

$$V_b = V_{ph} \cdot N_b/N_{ph} \qquad (1)$$

Where N_b is the number of turns in the bias winding 18 and

N_{ph} is the number of turns in the phase winding 16.

In physical terms, the bias winding may comprise a single winding spanning half an electrical pitch of the machine, as shown schematically in Figure 6(a) for the example of a machine having six stator poles 61 and four rotor poles 64. A rotor 66 is mounted on a shaft 68 to rotate within the stator. The stator poles carry coils 63, which are connected in series or parallel to provide three phase windings, one of which is represented as 16 in Figure 5. The bias winding 18 comprises a single coil 65 placed across the diameter of the machine, therefore embracing half the poles in a diametrically arranged loop.

Alternatively, as shown in Figure 6(b), the bias winding may comprise multiple coils 65' on all, or at least some, of the poles, each embracing the pole in the same way as, but distinct from the coils 63 of the phase winding 16 on the same pole. The coils 65' are connected in series so that the current in each one is the same. In this case, the series connection of the six bias coils is the equivalent of the single coil 65 in Figure 6(a).

It will be seen by inspection of the flux paths that these two arrangements are magnetically similar, and the choice between them would result from a consideration of such factors as size of the end-windings and the available space in the machine.

Other forms of bias winding may be used. For example, the winding may comprise gramme-ring type windings around the back-iron of the stator in which magneto motive force supporting the bias flux is applied around the back iron. In all cases, however, the bias winding sets up a flux from one half of the electrical pitch of the machine towards the other. For all these different bias winding arrangements the flux pattern at the air gap is the same. In a polyphase machine, the total flux will be essentially constant in magnitude for a constant bias current. As an alternative source of bias flux, a permanent magnet could be used in place of the bias winding 18, but such an arrangement would lack the flexibility of a wound coil in which the current can

be controlled.

The operation of the machine will now be explained using the circuit of Figure 5. To simplify the description, it will be assumed that the machine is magnetically linear. It is also assumed that the current source 20 is ideal in that it holds the bias current I_b constant regardless of any voltage induced in the bias winding 18. The switches 21 and 22 are open.

The inductance profile of phase winding 16 is shown in Figure 7. The profile is defined by the magnetic geometry of the laminations of the machine. Since inductance is defined as flux-linkage per amp of excitation, the flux in the phase winding is given by

$$\psi_{ph} = L\, I_b \qquad (2)$$

and is shown in Figure 7 for an arbitrary value of I_b. It follows that, for constant current I_b, the flux-linkage curve has the same form as the inductance. From Faraday's Law, the voltage induced in the phase winding is deduced as

$$V_{ph} = d\psi_{ph} / dt = \omega\, d\psi_{ph} / d\theta \qquad (3)$$

where θ is the angular displacement of the rotor and ω is the speed, $d\theta/dt$. Since the slope of the inductance profile is piecewise linear, the induced voltage has the rectangular form shown in Figure 7. The magnitude of the voltage, from Equations 2 and 3, is proportional to the speed and the bias current. As the voltage is increased, there comes a point where it equals the (constant) magnitude of the DC link voltage. By inspection of Figure 5, the diodes 23,24 will become forward biased when the negative voltage excursion equals the DC link voltage, thus clamping the phase voltage. This is shown in Figure 8. By Equation 3, the clamping of V_{ph} clamps $d\psi_{ph} / dt$ to a shallower slope, as shown by line Y, than it would otherwise have had, as shown by line X. The difference in flux-linkage between the two lines represents a flux which has to be supported by a current flowing in the diodes, as shown. Note that the voltage

waveforms and current waveforms are asymmetrical.

Since the switches 21 and 22 are not used, the circuit optionally is simplified to that shown in Figure 9(a) or 9(b) if the machine is not used in the motoring mode. This yields a power converter for a variable reluctance generator which has no active switches connecting it to the DC link. The DC link capacitor 25 may be replaced by a resistor 90 which simply dissipates the generated energy, allowing the system to be used as a brushless brake. In this case, the diodes clamp the negative excursion of the voltage to –IR, which is initially zero. Alternatively, the capacitor 25 optionally is replaced by a storage battery.

In another embodiment of the invention, shown in Figure 10, the diodes 23 and 24 are reconnected to replace the switches 21 and 22. As before, one or the other of the diodes optionally is deleted. This embodiment clamps the positive-going voltage excursion to the DC link voltage, so the gradient of the increasing flux is modified, as shown in Figure 11. In this case, the flux linkage is reduced from what it would otherwise be, so the current flowing is in the opposite direction in the phase winding. Because the new flux linkage line falls underneath the dead zone of the inductance profile, the shape of the current is different from that described earlier.

It is possible to combine the currents of Figure 8 and Figure 11 by using four diodes connected as in Figure 12. These are effectively connected in the form of a single-phase bridge, so it would be possible to use a standard component package for this duty.

Figure 13 shows the current waveforms of Figures 8 and 11 combined to give the current flowing in the DC link. It will be noted that the action of combining the currents delays the start of current from Figure 8, and that the composite waveform is discontinuous in part of the minimum inductance region. As the bias current or the speed is increased or the DC link voltage

is decreased, there comes a point, shown in Figure 14, beyond which current is always supplied from one or other pair of diodes.

A further increase in excitation or speed or further reduction of the DC link voltage brings the machine into a new operating mode, which it enters through a transient state. In this respect, it is akin to the continuous current mode of conventional switched reluctance drive systems as disclosed in EP 0537761A which is incorporated herein by reference. When a steady state has been reached, as shown in Figure 15 for an ideal system neglecting resistance, the length of time the flux takes to increase is exactly matched by the length of time taken to decrease and the locus of the point of change from increasing to decreasing follows the original flux linkage decrease. Since the slopes of increase and decrease are identical, the operating point is defined for any excitation level. Note that the two diode currents are still, in general, unequal, since the inductance profile is not symmetrical about a horizontal axis. This mode is inherently stable, since any perturbation will drive the increasing flux-linkage line to a smaller value and the decreasing flux-linkage line to a larger value, thus stabilizing the system.

It will be noted that the system described above has no need of shaft position information, since the diodes self-commutate when the currents fall to zero. This represents a further cost saving. It will be noted that in the embodiments shown there is no connection between the bias winding and the phase windings of the machine, i.e. there is galvanic isolation between them. This may be a significant safety benefit.

It will be appreciated that, while a single phase of a system has been used for illustration above, this is purely exemplary and the principles outlined above apply to any number of phases and any combination of numbers of stator and rotor poles. Where the system has three or more phases, alternative connections to the DC link are possible. For example, for a three-phase

system, delta or star (wye) connections are possible, as shown in Figure 16(a) and (b) respectively. Because the phase voltages are not symmetrical, the phase voltages in the delta connection only sum to zero under certain special conditions, so in general a circulating current will be present in the delta to compensate. Similarly, since the currents are not symmetrical, the phase currents in the star connection will only be equal under special conditions, so in general the star point will move to accommodate this. With these connections, the diodes form a standard three-phase bridge, so, again, a standard component module optionally is used.

Those skilled in the art will recognize that for phase numbers above three, corresponding ring and radial circuits are also possible.

In general, phase-controlled devices, such as thyristors or other silicon-controlled rectifiers, could be used to replace some or all of the diodes to give a further degree of control. While such a system would still not require rotor position information (since the devices would turn off when the current crossed zero), it would introduce a complexity which runs counter to the simplicity of embodiments of the invention.

In operation, it is assumed that the prime mover will spin the generator at some appropriate speed. In one embodiment of starting generating action, the control system causes the appropriate level of current to flow in the bias winding. Current is then generated onto the DC link, the amount of power transferred being controlled by adjusting the speed of the machine and/or the magnitude of the bias current. Those skilled in the art will appreciate that conventional feedback methods optionally are used to control the output. Other embodiments use modulation of the DC link.

The descriptions above have been on the basis of a controlled unidirectional bias current I_b. This is likely to be the most useful embodiment of the invention, though it should be noted

that it is possible to operate with uncontrolled or alternating bias current. The profile of the phase flux-linkage will have a superimposed modulation which, depending on the length of the period of the alternating bias current compared with the period of the inductance cycle of the variable reluctance machine, will result in a corresponding modulation of the generated current. For the special case of the period of the bias current corresponding to the period of the phase flux linkage, there is an opportunity to reduce the number of diodes in the circuit, though this benefit is likely to be offset by the complexity of synchronizing the two frequencies.

While the circuits of Figures 9, 10, 12 & 16 have dispensed with the active switches used in the motoring mode, it will be clear that if they are retained the system optionally is operated as a generator both according to embodiments of the invention and in a conventional switching mode without any re-configuration of the power converter.

The skilled person will appreciate that variation of the disclosed arrangements are possible without departing from the invention. Accordingly, the above description of several embodiments is made by way of example and not for the purposes of limitation. It will be clear to the skilled person that minor modifications can be made to the arrangements without significant changes to the operation described above.